3. Development of Lifeline Vulnerability Functions

3.1 Introduction

Vulnerability functions are used to describe the expected or assumed earthquake performance characteristics of each lifeline as well as the time required to restore damaged facilities to their pre-earthquake capacity, or usability. Functions have been developed for each lifeline inventoried for this project, or estimated by proxy (see Chapter 2). The components of each vulnerability function and how they were developed are described herein in Chapter 3. The functions themselves, too lengthy to include in this chapter, are provided in Appendix B.

The vulnerability function for each lifeline consists of the following components:

- *General* information, which consists of (1) a *description* of the structure and its main components, (2) *typical seismic damage* in qualitative terms, and (3) *seismically resistant design* characteristics for the facility and its components in particular. This information has been included to define the assumed characteristics and expected performance of each facility and to make the functions more widely applicable (i.e., applicable for other investigations by other researchers).

- *Direct damage* information, which consists of (1) a description of its basis in terms of structure type and quality of construction (degree of seismic resistance), (2) default estimates of the quality of construction for present conditions, and corresponding *motion-damage curves*, (3) default estimates of the quality of construction for upgraded conditions, and (4) *restoration curves*. As described below, these curves are based on data developed under the ATC-13 project (ATC, 1985).

In the following sections we describe the general approach and specific methodology utilized to develop the quantitative relationships for each vulnerability function (Direct Damage versus Modified Mercalli Intensity and Residual Capacity versus Modified Mercalli Intensity). Example computations are provided. In addition, a sample of a complete vulnerability function (*general information* plus *direct damage information*) is included as an illustrative example.

3.2 General Approach for Characterizing Earthquake Performance

The lifeline facility vulnerability functions used for this project are based on those developed on the basis of expert opinion in the ATC-13 project (*Earthquake Damage Evaluation Data for California*, ATC 1985). The ATC-13 direct damage data, presented in the form of Damage Probability Matrices (DPMs, Table 3-1), are applicable for Standard construction in California, as defined below, and may be modified per procedures outlined in ATC-13, which shifts the curves one-to-two intensity units down for Special construction, as defined below (i.e., -1 or -2), and one to two intensity units up for Nonstandard construction, as defined below (i.e., +1 or +2). Standard construction is defined (in ATC-13) to include all facilities except those designated as Special or Nonstandard. Special construction refers to facilities that have special earthquake damage control features. Nonstandard refers to facilities that are more susceptible to earthquake damage than those of Standard construction. Older facilities designed prior to modern design code seismic requirements or those facilities designed after the introduction of modern code seismic requirements but without their benefit can be assumed to be Nonstandard. In exceptional cases, older facilities may have had special attention paid to seismic forces and may qualify as Standard construction. While Special is defined in ATC-13 to refer to facilities that have special earthquake damage control features, in this study we take this to include, in some cases, facilities designed according to the most modern design code seismic requirements. Standard is assumed to represent existing California

Table 3-1 Typical ATC-13 Damage Probability Matrix (ATC, 1985) (Example for Liquid Storage Tanks, on ground)

Central Damage Factor	*Modified Mercalli Intensity*						
	VI	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*
0.00	94.0	2.5	0.4	***	***	***	***
0.50	6.0	92.9	30.6	2.1	***	***	***
5.00	***	4.6	69.0	94.6	25.7	2.5	0.2
20.00	***	***	***	3.3	69.3	58.1	27.4
45.00	***	***	***	***	5.0	39.1	69.4
80.00	***	***	***	***	***	0.3	3.0
100.00	***	***	***	***	***	***	***

***Very small probability

facilities (i.e., a composite of older non-seismically designed facilities, more recent facilities designed to the seismic requirements of their day, and modern facilities designed to current seismic requirements).

With regard to regional U.S. seismic design practice, the general consensus appears to be that, with few exceptions, only California and portions of Alaska and the Puget Sound region have had seismic requirements incorporated into the design of local facilities for any significant period of time. For all other areas of the United States, present facilities are assumed to have seismic resistance less than or equal to (depending on the specific facility) that of equivalent facilities in California NEHRP Map Area 7 (Figure 3-1) (ATC, 1978; BSSC, 1988). In this regard, we have broken the United States into three regions:

a. California NEHRP Map Area 7 (the general focus of ATC-13), which we take to be the only region of the United States with a significant history of lifeline seismic design for great earthquakes,

b. California NEHRP Map Areas 3-6, Non-California Map Area 7 (parts of Alaska, Nevada, Idaho, Montana, and Wyoming), and Puget Sound NEHRP Map Area 5, which we take to be the only regions of the United States with a significant history of lifeline seismic design for major (as opposed to great) earthquakes, and

c. All other parts of the United States, which we assume have not had a significant history of lifeline seismic design for major earthquakes.

As an example, examine on-ground liquid storage tanks (ATC-13 Facility Class 43, Table 3-1), for which ATC-13 indicates mean damage from ground shaking of Modified Mercalli Intensity (MMI) IX to be 4.6% of replacement value for Standard construction. If the construction is modern and judged to be Special construction, then the mean damage is indicated to be 0.5% (corresponding to MMI VII) for the same intensity of ground shaking. Alternatively, if the construction is judged to be Nonstandard (e.g., predating seismic design), then the mean damage is indicated to be 27.9% (corresponding to MMI XI) for the same intensity of ground shaking.

3.3 Method for Obtaining Lifeline Direct Damage and Residual Capacity Functions

This section presents the calculational algorithms employed in obtaining the quantitative lifeline component vulnerability functions for use in the ATC-25 project. Two vulnerability functions are determined: (1) direct damage to a lifeline component, in terms of repair costs expressed as a fraction or percentage of value, and (2) fraction of initial capacity (restored or remaining) as a function of elapsed time since the earthquake, for a given

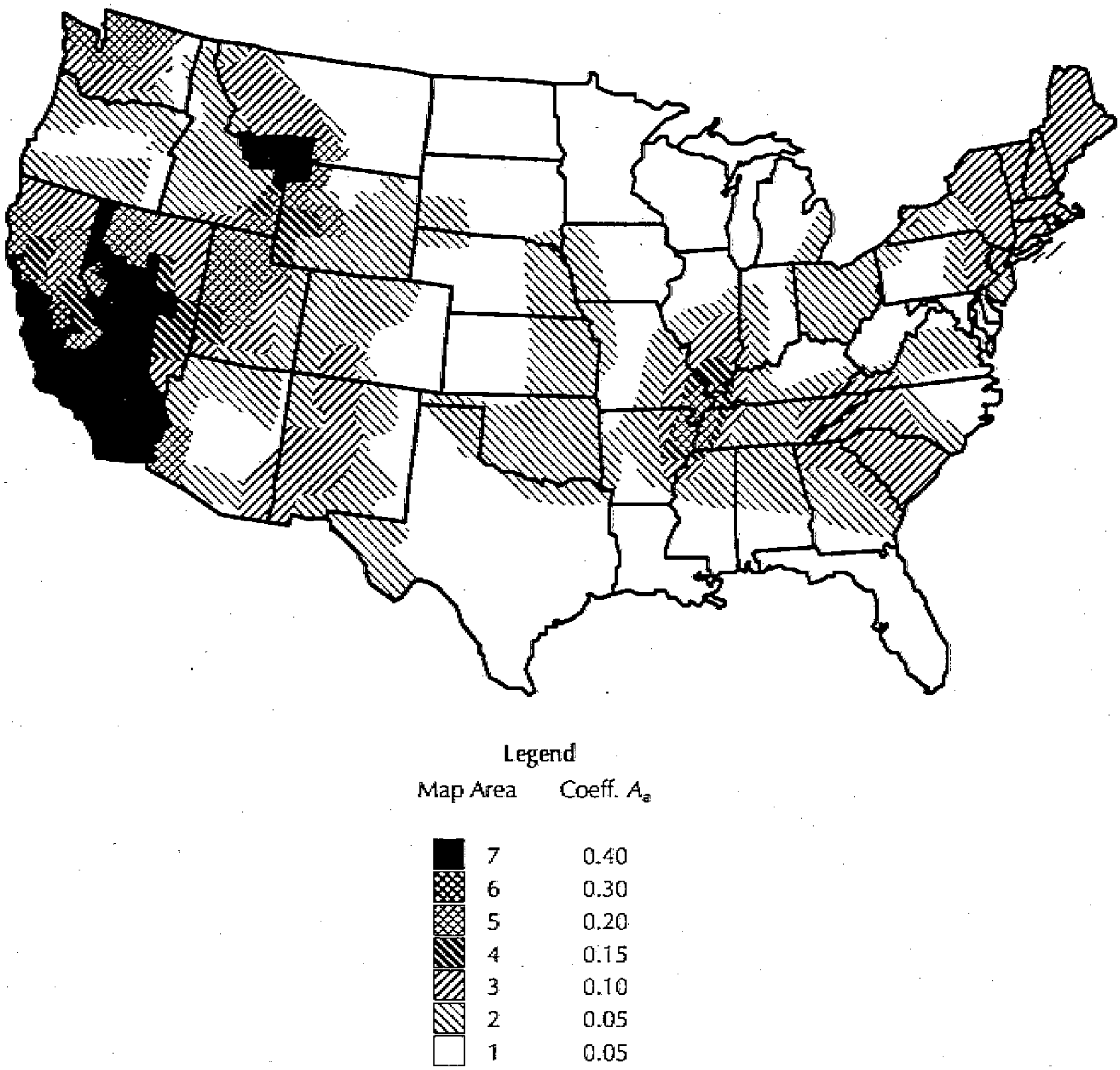

Figure 3-1 *NEHRP Seismic Map Areas (ATC, 1978; BSSC, 1988).*

MMI, herein termed restoration curves. All assumptions operative in ATC-13, such as unlimited resources for repair and restoration, apply to these results.

Three main steps are involved in obtaining the vulnerability functions for each component. Each of these steps is described below.

STEP 1

In order to obtain a continuous relation between seismic damage (DMG) and intensity (MMI), a regression of the form

$$DMG = \exp(a)\, MMI^{b} \tag{3.1}$$

is performed on the damage data points in Appendix G of ATC-13. The regression coefficients a and b are obtained for each Facility Class (FC) corresponding to a lifeline component. A damage curve of the form shown in Figure 3-2 is thus obtained for each Facility Class in ATC-13.

STEP 2

Data on time-to-restoration for different Social Function (SF) classes, which are facility types defined in terms of the four-digit Standard Industrial Classifications of the U. S. Department of Commerce, (provided in Table 9.11 of ATC-13), are used to perform the following regression, which gives a continuous relation between the damage state and the corresponding restoration time for each social function class:

$$T_R = \exp(c)\, DMG^{d} \tag{3.2}$$

where:

T_R = restoration time, in days
DMG = Central Damage Factor (CDF) for each damage state (DS)
c, d = regression coefficients

Regressions of the above form are performed for each of the social function classes using the data in ATC-13 on restoration times for 30%, 60%, and 100% restoration.

Thus,

$$T_{R=0.3} = \exp(c1)\, DMG^{d1}$$
$$T_{R=0.6} = \exp(c2)\, DMG^{d2}$$
$$T_{R=1.0} = \exp(c3)\, DMG^{d3}$$

Figure 3-3 shows the form of the regression curves we obtained.

STEP 3

The regressions obtained from the previous two steps are used to arrive at the restoration curves. The restoration curve for each lifeline component, for each intensity (MMI), is obtained by fitting a straight line through the three points corresponding to 30%, 60%, and 100% restoration time. The regression line has the following form:

$$R = f + (g)(T_R) \tag{3.3}$$

where:

R = % restored
T_R = restoration time, in days
f, g = regression coefficients

The three points used to fit a straight line by the above regression are obtained in the manner described below:

For a given lifeline component, the damage corresponding to a particular MMI is assumed to have a lognormal distribution. The time to restoration is then obtained numerically as the weighted average of the restoration time (given by Equation 3.2) taken over equal intervals of the lognormal distribution of the damage. The weight factors are the areas of the equal intervals of the lognormal distribution, i. e., the probabilities of the corresponding damage. For example,

$$T_R(30\%\ R, MMI) = \sum_{i=1}^{N} \left(p_i \times \exp(c1) \times DMG_i(MMI)^{d1}\right) \tag{3.4}$$

where $T_R(30\%\ R, MMI))$ is the restoration time to 30% restoration for a given MMI, p_i is the probability that the damage = DMG_i, i.e., the area of the interval, i, on the lognormal distribution of the damage, and N is the number of intervals of the lognormal distribution.

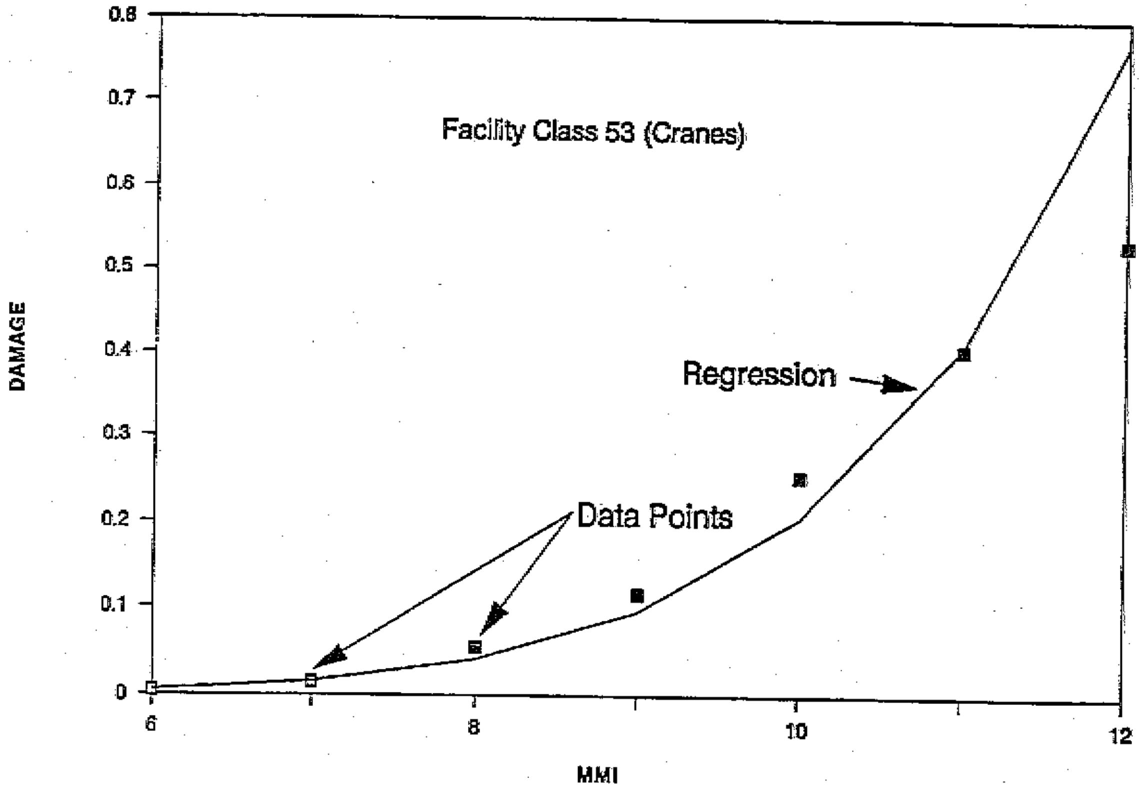

Figure 3-2 Comparison of ATC-13 Appendix G data (Statistics of Expert Responses for Motion-Damage Relationships) versus regression curve.

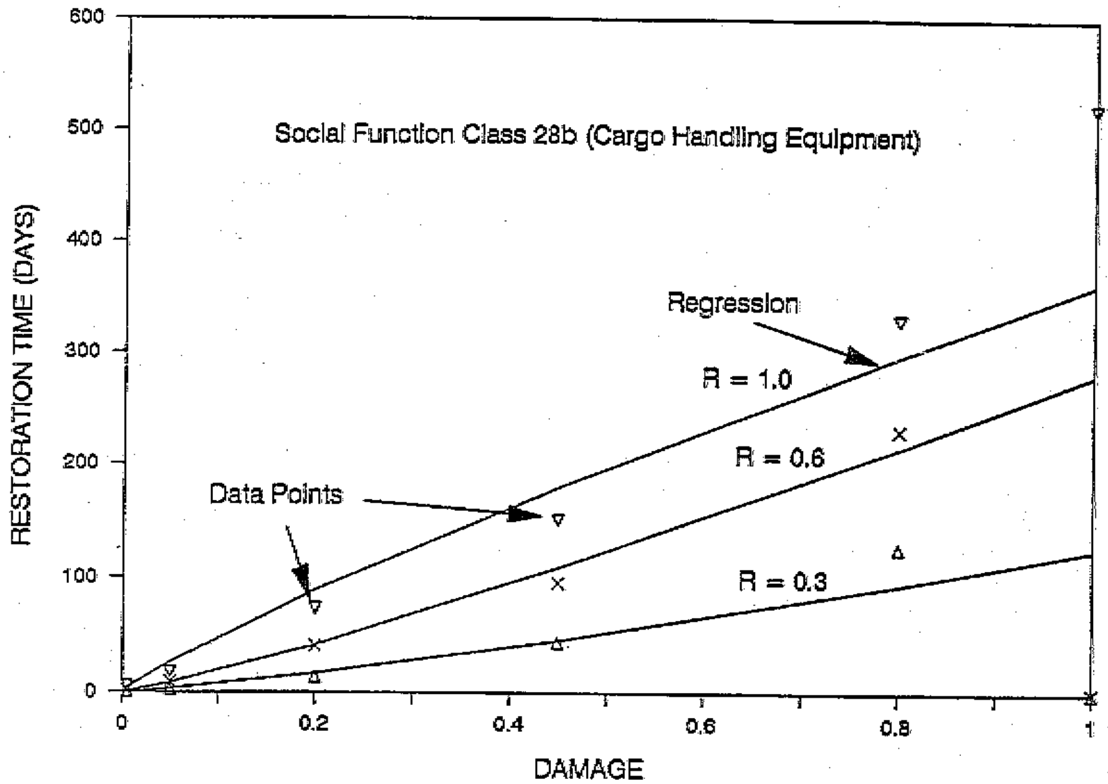

Figure 3-3 Comparison of ATC-13 Table 9.1 data (Weighted Statistics for Loss of Function Restoration Time of Social Function Classifications) versus regression curve.

Similar calculations are also carried out for 60% R and for 100% R.

Next, the weighted average of T_R(30%R, MMI) for the different social function classes corresponding to the lifeline component is obtained. This serves as one of the three points for fitting the restoration curve. The other two points are obtained by repeating the process for 60% and 100% restoration time. The regression line given by Equation 3.3, obtained using these three data points, is the restoration curve for the lifeline component. An example to illustrate the method of obtaining

(1) the direct damage curve and

(2) the restoration curves, for the Ports/Cargo Handling Equipment component of the Sea/Water Transportation lifeline

is provided below.

3.4 Example Direct Damage and Residual Capacity Computations

The following example illustrates the method of obtaining (1) the direct damage curve, and (2) the restoration curves, for the Ports/Cargo Handling Equipment component of the Sea/Water Transportation lifeline. Ports/Cargo Handling Equipment are typically container or general cargo cranes on piers. This component is taken to be composed of two ATC-13 Social Function Classes: 28a (Ports) and 28b (Cargo Handling Equipment), and of two Facility Classes: 63 (Waterfront Structures) and 53 (Cranes), weighted by the factors indicated in Table 3-2.

STEP 1

Regression coefficients for seismic damage are computed from Equation 3.1 for each Facility Class (FC) as follows:

Facility Class		Regression Coefficient	
Class	Factor	a	b
63	0.6	-20.0847	8.0976
53	0.4	-18.2783	7.2508

The damage regression curve obtained in this manner is illustrated in Figure 3-2 for Facility Class 53 (Cranes). The values for the damage are listed below, together with the ATC-13 data (from ATC-13, Appendix G, weighted mean of best estimate of damage factor):

Table 3-2 Weighting Factors Used to Determine Percent of Social Function and Facility Classes Contributing to Ports/Cargo Handling Equipment

Social Function Class	Factor	Facility Class	Factor
28a	0.6	63	0.6
28b	0.4	53	0.4

MMI	DMG (ATC-13)	Regr (DMG)
6	0.004	0.005
7	0.014	0.015
8	0.055	0.041
9	0.117	0.096
10	0.253	0.205
11	0.406	0.410
12	0.535	0.771

The damage curve for the component as a whole is obtained by calculating, for each MMI, the weighted average of the damage for each of the facility classes corresponding to the component.

$$\begin{aligned} \text{DMG} &= e^{a1}\text{MMI}^{b1} \, x \, \text{factor}(1) + e^{a2}\text{MMI}^{b2} \, x \, \text{factor}(2) \\ &= 0.101 \, x \, 0.6 + 0.096 \, x \, 0.4 \\ &= 0.099 \text{ for MMI} = \text{IX} \end{aligned}$$

STEP 2

Regression coefficients for restoration time are computed from Equation 3.2 as follows:

	Regression Coefficients			
	Social Function 28a		Social Function 28b	
Restor-ation %	c	d	c	d
30%	6.4575	2.7162	4.8240	1.2514
60%	5.4769	1.1671	5.6373	1.1880
100%	6.1996	1.0445	5.8890	0.8725

The values for the time to 30% restoration, for the Social Function Class 28b are listed below, together with the ATC-13 data from Table 9.11:

DMG	ATC-13	Regression Values
0.005	0.2	0.1643
0.05	2.3	2.93
0.2	13.3	16.61
0.45	44.4	45.82
0.8	127.0	94.14
1.0	*	125.46

*No statistics provided.

Figure 3-3 shows the curves obtained by the above regressions, as well as the ATC-13 mean data points.

STEP 3

Mean restoration times for each Facility Class (FC) are obtained from Equation 3.4 as follows:

Mean Restoration time =

$$\sum_{i=1}^{N} [p_i \exp(c)\, DMG_i^{d}]$$

where c and d are given above for 30%, 60%, and 100% restoration.

For MMI = XI, for example, mean restoration times are computed as follows:

	T_R=0.3	T_R=0.6	T_R=1.0
FC = 28a	79.73	93.20	211.23
FC = 28b	45.45	107.66	177.27
Mean T_R	66.02*	98.98	197.65

*e.g., Mean T_R = 79.73 x 0.6 + 45.45 x 0.4 = 66.02

(Note: P_i is 1/N where N is the number of intervals used to divide the lognormal distribution of the damage; N=100 in this example and DMG_i is the corresponding damage value for each interval, i.)

The final restoration curve for MMI = XI is the best-fit straight line using Equation 3.3 through the 3 points corresponding to restoration times 66.02, 98.98, and 197.65 days. In this case, the regression equation is as follows:

$$R = 0.026 + 0.005\,(T_R)$$

Determination of these relations permits calculation of residual capacity of the lifeline as a function of time. From the above equation we see that Ports/Cargo Handling Equipment subjected to MMI XI will be restored to approximately 18% of pre-earthquake capacity after 30 days, and to 48% approximately 90 days after the earthquake.

3.5 Sample Lifeline Vulnerability Function

Following is a sample of a complete lifeline vulnerability function for ports/cargo handling equipment. Complete vulnerability functions for all lifelines are given in Appendix B.

3.5.1 Ports/Cargo Handling Equipment

1. General

Description: In general, ports/cargo handling equipment comprise buildings (predominantly warehouses), waterfront structures, cargo handling equipment, paved aprons, conveyors, scales, tanks, silos, pipelines, railroad terminals, and support services. Building type varies, with steel frame being a common construction type. Waterfront structures include quay walls, sheet-pile bulkheads, and pile-supported piers. Quay walls are essentially waterfront masonry or caisson walls with earth fills behind them. Piers are commonly wood or concrete construction and often include batter piles to resist lateral transverse loads. Cargo handling equipment for loading and unloading ships includes cranes for containers, bulk loaders for bulk goods, and pumps for fuels. Additional handling equipment is used for transporting goods throughout port areas.

Typical Seismic Damage: By far the most significant source of earthquake-induced damage to port and harbor facilities has been pore-water pressure buildup in the saturated cohesionless soils that prevail at these facilities. This pressure buildup can lead to application of excessive lateral pressures to quay walls by backfill materials, liquefaction, and massive submarine sliding. Buildings in port areas are subject to generic damage due to shaking, as well as damage caused by loss of bearing or lateral movement of foundation soils. Past earthquakes have caused substantial lateral sliding, deformation, and tilting of quay walls and sheet-pile bulkheads. Block-type quay walls are vulnerable to earthquake-induced sliding between layers of blocks. This damage has often been accompanied by extensive settlement and cracking of paved aprons. The principal failure mode of sheet-pile bulkheads has been insufficient anchor resistance, primarily because the anchors were installed at shallow depths, where backfill is most susceptible to a loss of strength due to pore-water pressure buildup and liquefaction. Insufficient distance between the anchor and the bulkhead wall can also lead to failure. Pile-supported docks typically perform well, unless soil failures such as major submarine landslides occur. In such cases, piers have undergone extensive sliding and buckling and yielding of pile supports. Batter piles have damaged pier pile caps and decking because of their large lateral stiffness. Cranes can be derailed or overturned by shaking or soil failures. Toppling cranes can damage adjacent structures or other facilities. Misaligned crane rails can damage wheel assemblies and immobilize cranes. Tanks containing fuel can rupture and spill their contents into the water, presenting fire hazards. Pipelines from storage tanks to docks can be ruptured where they cross areas of structurally poor ground in the vicinity of docks. Failure of access roads and railway tracks can severely limit port operations. Port facilities, especially on the West Coast, are also subject to tsunami hazard.

Seismically Resistant Design: At locations where earthquakes occur relatively frequently the current design practice is to use seismic factors included in local building codes for the design of port structures. However, past earthquakes have indicated that the seismic coefficients used for design are of secondary importance when compared to the potential for liquefaction of the site soil materials. Quay wall and sheet-pile bulkhead performance could be enhanced by replacing weak soils with dense soils, or designing these structures to withstand the combination of earthquake-induced dynamic water pressures and pressures due to liquefied fills. Pier behavior in earthquakes has been good primarily because they are designed for large horizontal berthing and live loads, and because they are not subject to the lateral soil pressures of the type applied to quay walls and bulkheads. However, effects on bearing capacity and lateral resistance of piles due to liquefaction and induced slope instability should also be considered.

2. Direct Damage

Basis: Damage curves for ports/cargo handling equipment in the sea/water transportation system are based on ATC-13 data for Facility Class 53, cranes, and Facility Class 63, waterfront structures. Ports/cargo handling equipment are assumed to be a combination of 60% waterfront structures and 40% cranes.

Standard construction is assumed to represent typical California ports/cargo handling equipment under present conditions (i.e., a composite of older and more modern ports/cargo handling equipment). Only minimal regional variation in construction quality is assumed, as seismic design is performed only for selected port structures, and soil performance is the most critical determinant in port performance.

Present Conditions: In the absence of data on the type of material, age, etc., the following factors were used to modify the mean curve for the two facility classes listed above, under present conditions:

	MMI Intensity Shift	
NEHRP Map Area	FC 53	FC 63
California 7	0	0
California 3-6	0	0
Non-California 7	0	0
Puget Sound 5	0	0
All other areas	+1	+1

The modified motion-damage curves for ports/cargo handling facilities are shown in Figure 3-4.

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to Social Function (SF) 28a, ports, and SF 28b, cargo handling equipment, were assumed to apply to all ports/cargo handling equipment. Ports/cargo handling facilities were assumed to be a combination of 60% ports and 40% cargo handling facilities. By combining these data with the damage curves derived using the data for FC 53 and 63, the time-to-restoration curves shown in Figures 3-5 and 3-6 were derived.

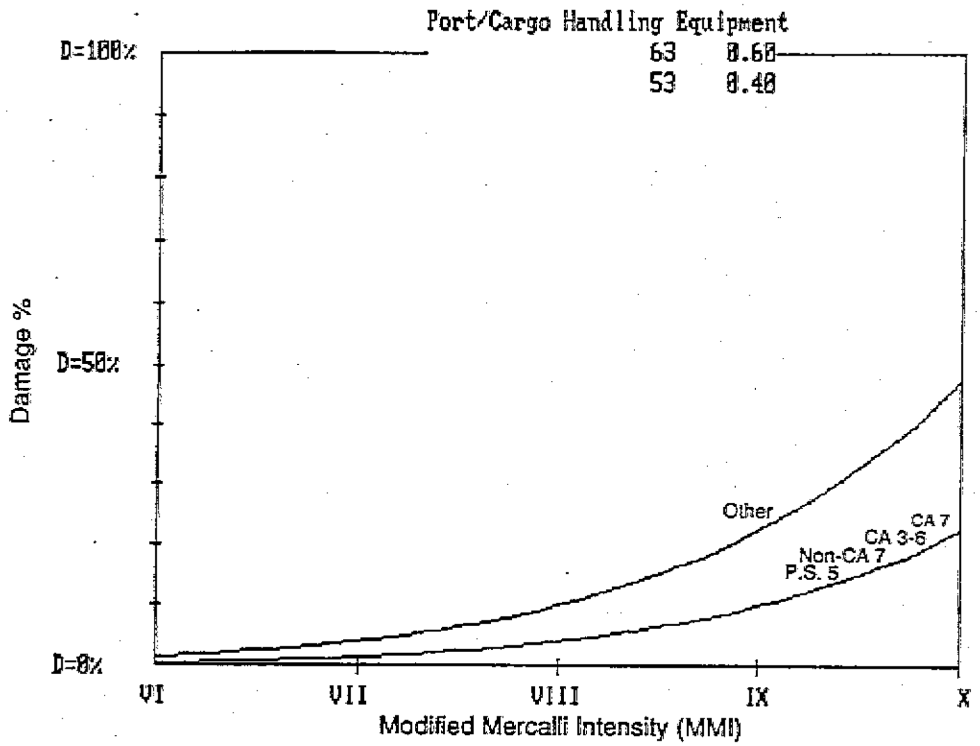

Figure 3-4 Damage percent by intensity for ports/cargo handling equipment.

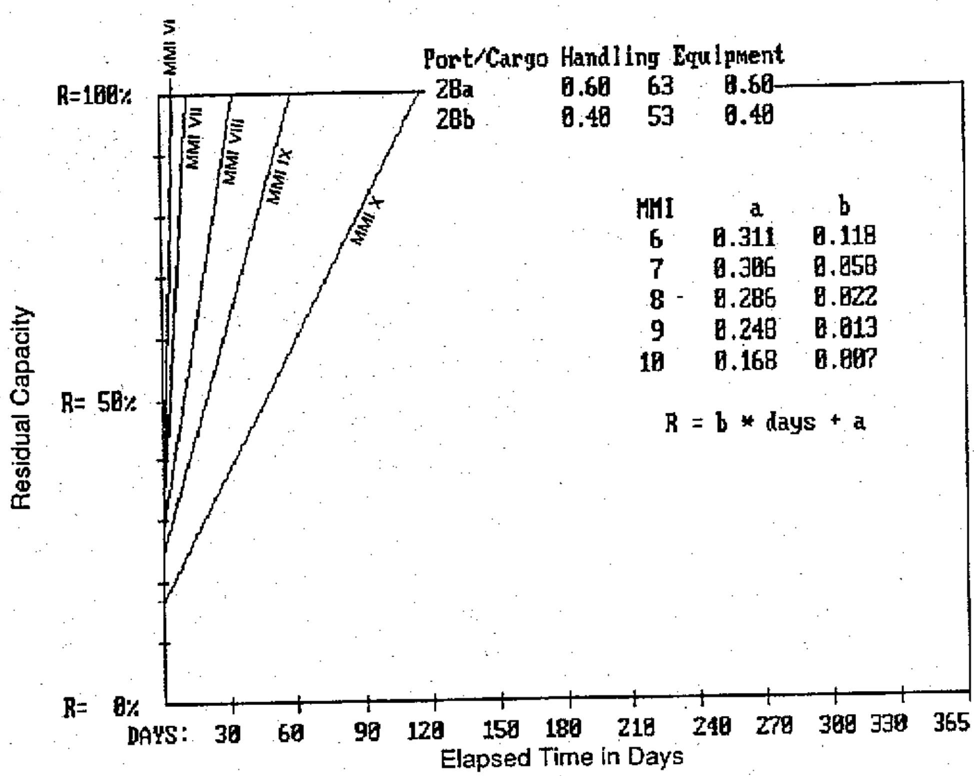

Figure 3-5 Residual capacity for ports/cargo handling equipment (NEHRP Map Area: California 3-5, California 7, Non-California 7, and Puget Sound 5).

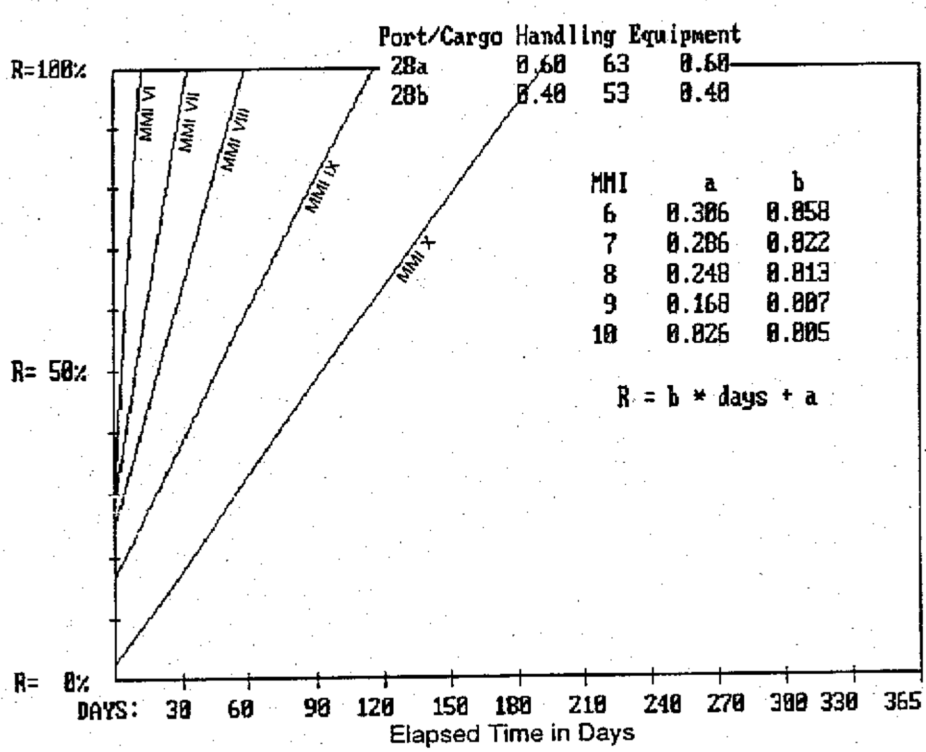

Figure 3-6 Residual capacity for ports/cargo handling equipment (all other areas).